Climate Change in Scotland: Impact on Mini-Hydro

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ABSTRACT
UK Government targets for renewable energy and the new Renewable Obligations suggest a renewed interest in mini-hydropower. However, changes in climate and, in particular precipitation, have been shown to significantly alter the quantity and distribution of river flows. Furthermore, these changes have been shown to impact on the production and, consequently, the economics of large hydropower schemes. The literature highlights that the sensitivity of production to changes in climate increases significantly as the amount of storage declines. Given that run-of-river mini-hydropower schemes have little or no storage they may be particularly vulnerable to the changes in river flow quantity and distribution that result from climate change. To assess the threat, a simple software model has been developed that enables an examination of the sensitivity of mini-hydro production and economics to climate change. A possible low-head scheme located in the Scottish Borders is used as a case study. The impact of altered precipitation and temperature on river flows, production and project economics are examined. Consideration is also given to the potential and desirability for making the project more climatically robust.

INTRODUCTION
To assist the United Kingdom (UK) to meet its obligations under the Kyoto Protocol and further reducing carbon dioxide (CO_2) emissions by 20% by 2010, the Governments has set targets for renewable energy generation. Under the Renewables Obligations (DTI, 2002; Scottish Executive, 2002a), electricity suppliers must ensure that 10% of the energy they provide to consumers in England and Wales (18% in Scotland) is derived from renewable resources. With existing large hydro explicitly excluded and new build unlikely, the energy must be generated from wind, wave, biomass or small- or mini-hydro plant. Production from these resources will be accompanied by Renewable Obligation Certificates (ROCs) which may be sold by generators to suppliers. The obligation encourages renewable developments as suppliers failing to purchase sufficient ROCs will be liable for buy-out penalties. This revenue earned from ROC sales significantly improves the economics of renewable resources particularly for mature technologies like hydro (Harrison, 2005).

While the 2010 renewables target is quite modest, the targets for later years are expected to be more significant: the UK has aspirations for 20% of demand by 2020 while the Scottish Executive is currently proposing a target of 40% (Scottish Executive, 2002b). Such targets will require the exploitation of much of the UK's renewable potential. In Scotland, the unconstrained potential has been estimated at around 59 GW of which some 300 MW is small hydro potential capable of producing energy at less than 7p/kWh (Garrad Hassan, 2001). Although many of the better sites for small and mini-hydro have already been developed and that other renewable technologies are or will become cheaper, there is still scope for development in Scotland and elsewhere.

While the Government's response to climate change may promote the development of small- and mini-hydro, the effects of climate change itself may not be in the best interests of this technology.

CLIMATE CHANGE AND MINI-HYDRO
A large and increasing body of work has highlighted the potential for predicted changes in climate and, in particular precipitation, to significantly alter the quantity and distribution of river flows (e.g. Arnell, 1996). Furthermore, these changes have been shown to impact on the production and, consequently, the economics of large hydropower schemes (Harrison and Whittington, 2002). The literature also indicates that the sensitivity of production to changes in climate increases significantly as the amount of storage declines. By definition, run-of-river (RoR) mini-hydropower schemes have little or no storage. Furthermore, they are designed from flow duration curves where there is a trade-off between harvesting high flows and remaining operational during low flows. Given that installations have normally only one turbine, the capability of mini-hydro to respond to changes in flow distribution is rather limited. These factors may lead mini-hydropower to be particularly vulnerable to the changes in river flow quantity and distribution that result from climate change.

The capacity and potential returns from mini-hydro schemes means that they have been largely neglected by large-scale developers and their construction has been predominately undertaken by smaller companies or individuals. With often only one plant in their portfolio, the failure of that plant, either physically or in terms of lower than expected revenue, has the potential to create great hardship or even insolvency for the investors. Hence, the lack of significant financial support makes the consequences of detrimental climate change perhaps more severe for smaller plant.

Despite the apparent sensitivity of mini-hydro to climate change it has largely been neglected in studies. This is partly because analysis has tended to concentrate on large-scale hydro in regionally or nationally significant river basins, presumably because impacts would initially appear to have the greatest impact. It is also because, when compared to the output of large-scale thermal and large hydro plant, the contribution of small-scale plant could be considered negligible. With the general trend towards smaller, geographically distributed renewable generation the contribution of small-scale plant will, in the future, no longer be considered negligible. As such it is important to determine the scale of the changes that global warming may bring and their impact on mini-hydro. In carrying out this exercise, particular attention has been given to the differing needs and issues of small hydro developments. The feasibility budgets of mini-hydro schemes means that extensive hydrological studies of climate change is unlikely to be possible. The aim here is to examine what may be achieved using techniques and ideas available to all would-be mini-hydro developers.

SCOTTISH BORDERS CASE STUDY

The potential mini-hydro scheme chosen is at Ormiston Mill on the River Teviot in the Scottish Borders (Figure 1). The potential of the site is identified in the Salford (1989) study of UK small hydro potential, which recommends a 240 kW machine operating on a 2m head to produce around 1,200 MWh annually. At present the weir has been partially removed (and lowered) although some of the original construction is evident near the entrance to the old mill lade which is also obscured and partially filled. The original sluice gates exist but are in a poor state of repair.

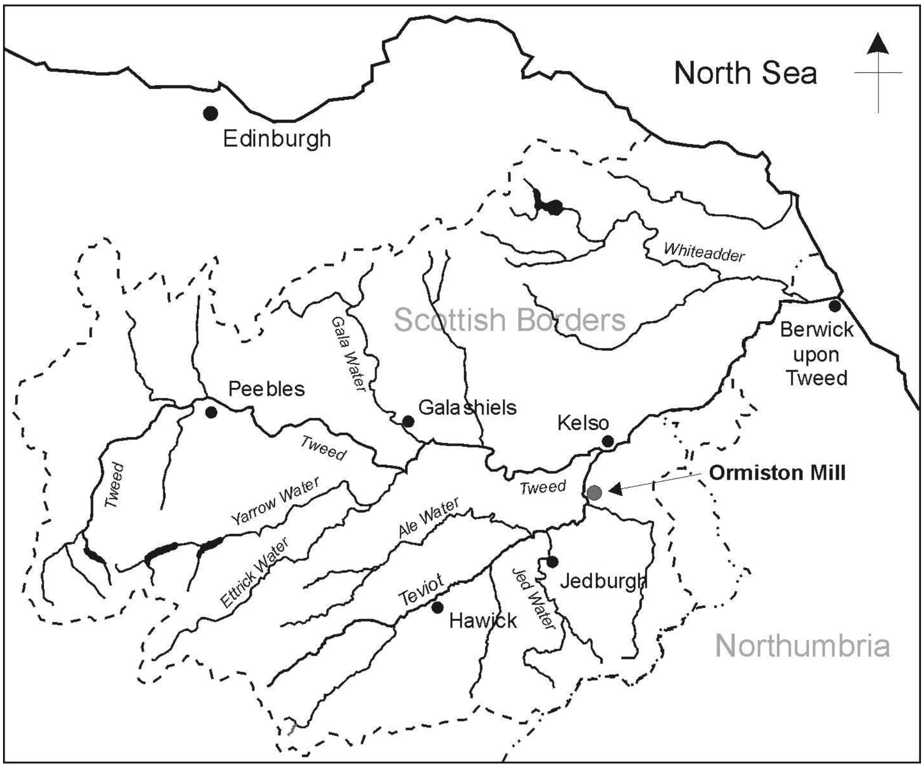

Figure 1. Case study catchment

The scheme is modelled in a spreadsheet version of software developed by Harrison and Whittington (2002) and has been simplified for use with run-of-river hydro schemes. It uses a monthly time step, in-line with the most readily available climate data. The model consists of several serially-connected components: a catchment model that converts climate time-series to estimates of river flows, and a run-of-river hydropower model that provides estimates of production, revenue and economic performance. The model was driven by a thirty year time series of climatic data covering the years 1961 to 1990 acquired from the National River Flow Archive at CEH Wallingford (NRFA, 2004). The data requirements include precipitation and temperature together with several others required for the calculation of potential evapotranspiration (PET). The model performs well although it has a tendency to overstate winter and spring flows.

The hydro scheme is modelled in a very simple manner with net head, crossflow turbine efficiencies, river flows and hence production assumed to be constant over each period. Turbine maximum and minimum flow limits are applied along with the requirement to provide compensation flow. For illustration, the plant capital costs were taken to be £1200/kW installed and the annual operations and maintenance cost is 3% of capital cost. Revenue is calculated on the basis of a flat rate payment of £60/MWh which includes both energy and the ROC. The key project performance parameters are given in Table 1.

Project Parameter	Value
Catchment area	1,110 km^2
Mean annual rainfall (1961-1990)	939 mm
Mean flow (1961 to 1990)	19.8 m^3/s
Mean monthly production	125 MWh
Payback period	7 years
Internal Rate of Return (IRR)	12.9%

Table 1. Key project parameters

CLIMATE SENSITIVITY

The simplest means of analysing the effect of climate change is to perform a sensitivity analysis. This involves uniformly altering precipitation and temperature time series across a range of changes and examining the outcomes for river flows, production and financial performance. Generally, one would want this range to encompass the extent of possible changes in climate that may occur. On a global scale we can expect a temperature rise of up to 5.8°C by the end of the century (IPCC, 2001). More locally, by 2080, this area of Scotland may experience annual mean temperatures that are 2.5 to 3.0°C higher than the 1961-1990 mean, while annual precipitation may increase by around 20% (Hulme et al, 2001). As such, increasing mean monthly temperatures by up to 4°C and altering precipitation by up to 20% will give an indication of how the Teviot catchment and a hydro scheme built at Ormiston Mill would respond to changes in climate over this century.

As would be expected, increased precipitation raises mean river flows whilst higher temperatures tend to lower flows. The effect of uniformly changing temperatures is limited to just over 0.6%/°C, while changes in precipitation lead to flow changes that are proportionately greater than the incident change in rainfall, an occurrence noted in many climate impact studies (Arnell, 1996). A 20% rise in precipitation coupled with a 4°C rise in temperature (defined as 'wet' conditions) delivers a 25% increase in mean monthly flows. The other extreme, that of a 20% decrease and the same warming (defined as the 'dry' conditions) creates a 28% decrease in flows. Figure 2 shows the variation of mean monthly river flow with changes in temperature and precipitation. The contours show combinations of temperature and precipitation and the resulting change in flow.

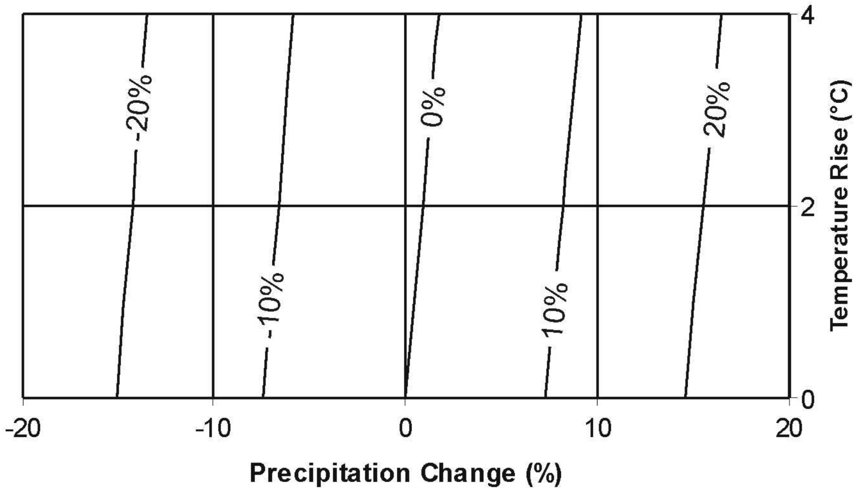

Figure 2. Percentage change in river flows with uniform changes in precipitation and temperature

The changes in river flows impact on production and, as Figure 3 indicates, production rises with precipitation. While the proportionate changes are smaller in magnitude than the changes in river flows, they are still significant: under dry conditions production falls by almost 20% while under wet conditions rises by over 9%. The smaller changes seen with increases in rainfall are due to the fact that proportionately greater durations are spent with the turbine operating at maximum capacity.

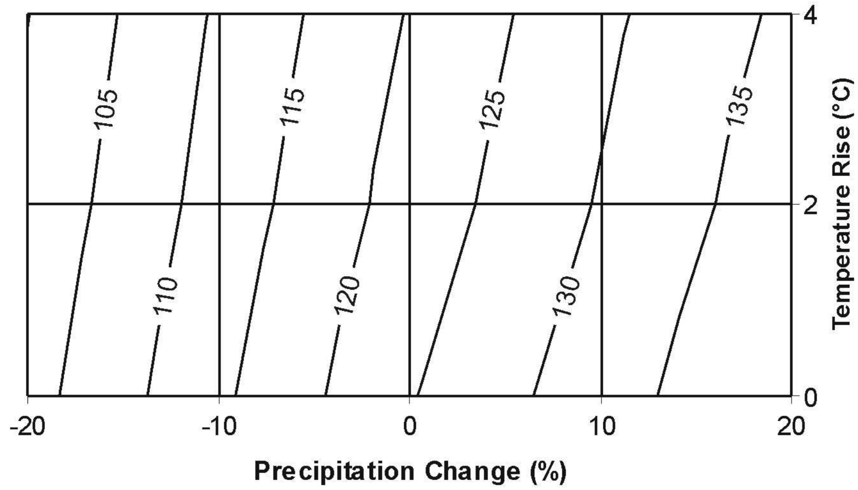

Figure 3. Mean monthly production (MWh) with uniform changes in precipitation and temperature

Revenue follows a similar pattern to production. However, with the relatively high capital costs, the Internal Rate of Return (IRR) is very sensitive to changes in precipitation, particularly reductions, as the tighter packed contours in the left hand side of Figure 4 indicate. Again for illustration, dry and wet conditions result in IRR changes of –29% and 13%, respectively.

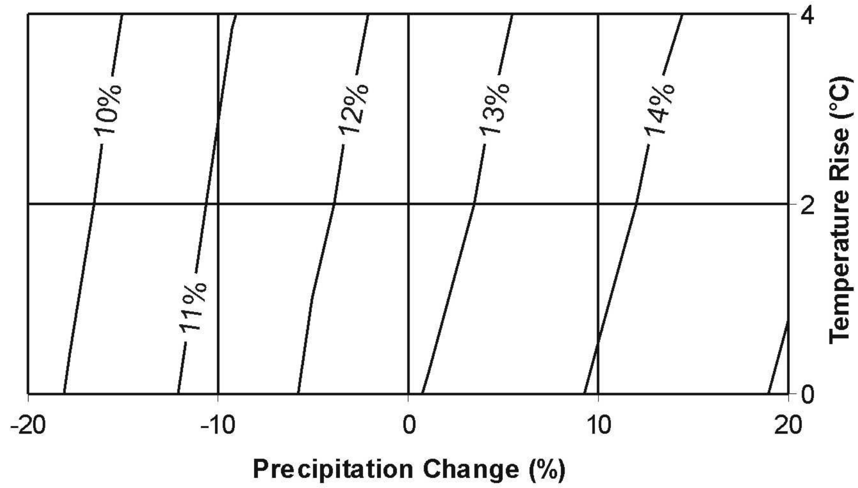

Figure 4. IRR (%) with uniform changes in precipitation and temperature

The key benefit of this approach is that it enables the identification of the project's critical climate variables, i.e. the combination of values of precipitation and temperature that result in the project becoming marginal in terms of its economic viability. Clearly, this is dependent on investor preferences and their minimum return requirements: the lower the minimum expected return the greater the margin of safety. As an example, this is assumed to be 10% with the critical climate values being those that deliver this IRR; the 10% contour line in Figure 4 shows such values. By inspection it is apparent that as temperatures rise, the tolerable decrease in precipitation is reduced: with no temperature rise the scheme can tolerate around an 18% reduction in rainfall but with 4°C rise the margin is reduced to just over 15%.

CLIMATE MODEL SCENARIOS

One of the key projections from climate models is that there will be significant seasonal differences in warming and precipitation changes. The uniform changes used earlier do not take these subtleties into account. For the UK there appears to be a general trend towards wetter winters and drier summers (UKCIP, 2002), exacerbating current seasonal differences. To illustrate these effects, projections from the UK's Hadley Centre Regional Model have been used. Although driven by a larger-scale model, the Regional model operates on a 50 km grid, providing a far higher resolution representation of current and future climates than the global climate models. Figures 5 and 6 show the annual, winter and summer changes in temperature and precipitation, respectively, expected by the 2020s assuming a scenario of continuing high levels of carbon emissions Within some of the diagrams there are portions of land that are coloured white within which the expected changes fall within the natural variability of the climate. All other shades indicate changes that are outside these limits and represent statistically significant changes in behaviour.

In Figure 5 it can be seen that for the majority of the UK and Ireland – including the area surrounding our case study – the annual warming is between 0.5 to 1°C. For the very south of England and the Continent the warming is half a degree higher still. In winter the warming is less pronounced but in the summer it is clear that a far larger part of the country will experience higher temperatures, albeit that the case study is fractionally too far to the north to fall into this zone.

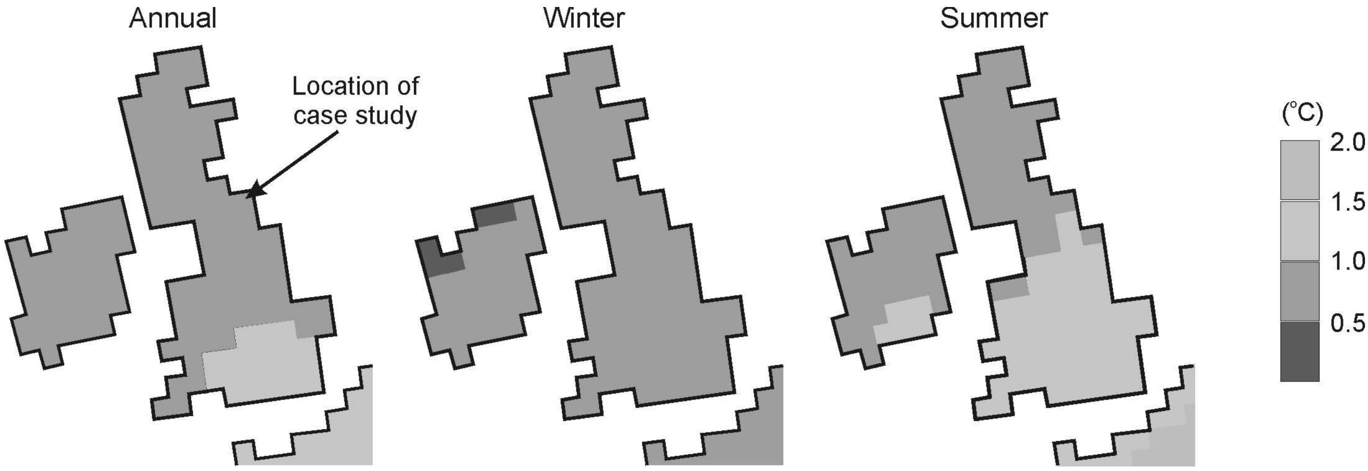

Figure 5. Annual and seasonal temperature change in the UK by 2020, adapted from UKCIP (2002)

Figure 6 shows that on an annual basis, there are decreases in precipitation of up to 10% over a significant fraction of the UK, particularly in the south and east. For much of the rest, there will be changes although these are not expected to be outside the range of the natural climate. The difference between winter and summer changes is remarkable. Winter rainfall is expected to increase by 10-15% for most of the UK (apart from western Scotland), with slightly larger increases in some parts of eastern Scotland. Summer will see a drying trend, with all but the west and north of Scotland seeing reductions in rainfall of between 10 and 20% and most of the remainder experiencing about half the level of change. In each of the projections the case study area is shown to experience significant seasonal and annual changes in precipitation.

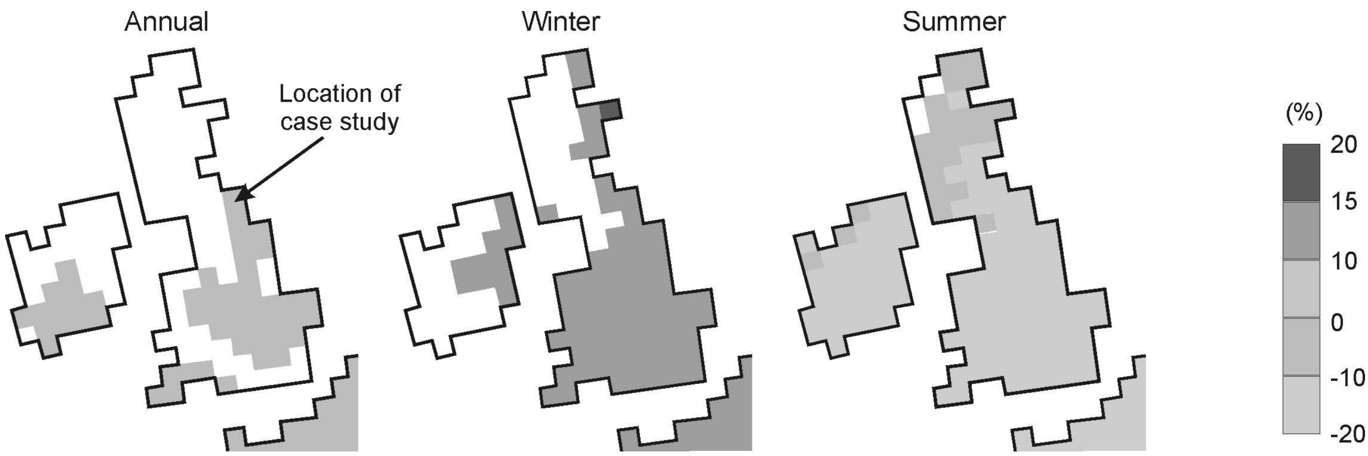

Figure 6. Annual and seasonal precipitation change in the UK by 2020, adapted from UKCIP (2002)

Hydro schemes built towards the 2010 and particular the 2020 targets will increasingly experience a climate closer to that of 2020 than the climate experienced over the later decades of the 20th century. Economically, the major issue is whether the scheme has repaid its debts. Plant built in the 1990s will likely have repaid its loans and so the risks of reduction in income through changes in climate will have a less significant effect. However, those commissioned towards 2010 and after would likely still be servicing debt.

Ideally, the way to assess future changes would be to take the time series output of many climate models and form a decision tree on the basis of the projected financial indicators. In this relatively simple example, the aim is to illustrate the effect of non-uniform changes in precipitation and temperature, rather than provide an exhaustive analysis. We can get a feel for the impact the changes projected for 2020 would have by re-running the spreadsheet model using the historic climate data and perturbing it using the forecast changes.

Table 2 shows the projected precipitation and temperature changes for the area in the vicinity of Ormiston Mill. The seasonal differences are clear and these have an effect on seasonal flow. While annual changes are relatively small, there is a clear increase in winter flows and an even greater decrease in summer flows. In production terms, the turbine capacity limit means that virtually no additional power is produced during the winter relative to current conditions. However, the significant drops in summer flows mean that the scheme is idle for more of the season and consequently production drops by over a fifth. Fortunately, the larger potential in winter means that annual production is impacted to a lesser degree although the drop is still appreciable. Financially, the impact of these conditions would be modest, reducing IRR by around 0.8 percentage points, well within the margin of safety.

Projected change	**Annual**	**Winter**	**Summer**
Temperature	+0.84°C	+0.57°C	+0.98°C
Precipitation	–1.84%	+4.84%	–9.45%
Monthly river flows	–1.73%	+4.51%	–13.74%
Mean production	–4.86%	+0.02%	–21.27%

Table 2. Projected changes in climate and implied changes in river flow and production

A rapid comparison with the earlier results from applying uniform changes in climate (Table 1) suggests that the earlier results underestimate the potential change. The annual changes in precipitation and temperature imply that production and IRR would decrease by about half that projected by the climate model scenario. This reinforces the idea that it is preferable to use climate scenario data where available.

ADAPTATION

The issue of adapting to climate change is a common theme across many vulnerable sectors. In the context of mini-hydro, what scope exists for adapting schemes to potentially altered river flow regimes by altering a project at the design stage or by retrofit at a later date? Adaptation at a river basin scale has been examined to some extent in Reibsame et al. (1995) which dealt with the management of climate impacts in the Zambezi. At the plant level, Weyman and Bruneau (1991) found that the least cost optimal design of a large hydro scheme in Quebec, Canada altered with climate change, as changes in river flows increased the marginal costs of the scheme and reduced the firm energy production. Various technical means have been suggested for reducing the impact of changes in flows on water supply and hydro production. These include increasing reservoir storage (Cole et al., 1991) which implies raising dam height, increasing turbine efficiencies and lowering intakes to increase active storage (Reibsame et al., 1995). There are, however, fewer options available for smaller, particularly low head, run-of-river schemes as:

- there is no storage to speak of,
- the low head limits the possibility of using alternative turbine types,
- future efficiency gains on crossflow turbines may be difficult, and
- increasing the weir height to raise the head would be costly and potentially environmentally unacceptable.

As such, the only real option is to vary the turbine capacity.

In this case and given that this climate model forecasts increased and more variable flows, an increase in the turbine capacity would enhance capture of the winter flows, albeit at the expense of raising the minimum flow requirements and reducing summer capture further. The selection of optimal turbine size is a standard component of small hydro planning and therefore consideration of this in the context of climate change is fairly similar. In this case, an additional incentive may be that winter-time production is more valuable. Hence, the ability to capture greater volumes of winter flows could be relatively beneficial although the cost implications of a larger turbine and potentially larger penstock would need to be considered. The question remains however, should a developer make decisions on the basis of a ‘potential’ change? Unfortunately, the framework for answering this question is rather complex and a demonstration of it is beyond the scope of this paper.

CONCLUSION

While the literature contains examples of climate impacts on the production and economics of larger schemes, little or no consideration has been given to the impact on smaller hydro, despite the fact that the lack of storage makes smaller hydro potentially more vulnerable to changes in river flows. Two example analyses have been applied to a potential mini-hydro scheme in the Scottish Borders; one a simple sensitivity study is useful for preliminary studies and identifying the tolerable change. Its failure to represent seasonal changes in climate means it may understate the potential changes although the application of change scenarios based on the output of global and preferably regional climate models goes some way to alleviating these difficulties. The need to consider multiple scenarios to cover the uncertainty inherent in climate impact assessments makes analysis and consideration of adaptation measures rather complex.

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